FORCE AND LAWS OF MOTION

Force:-Force is an interaction between two objects. Force may be defined as an influence, which tend to change state, speed, direction and shape of a body. It has both magnitude and direction and is therefore, a vector quantity. It may also be defined as an external agency, which changes the speed and direction of a body. It can also change the shape of a body.

Force is a vector quantity. It is represented by an arrow ($\vec{F}$).

Units of force: In S.I system, force is measured in Newton's represented by letter "N" while as in C.G.S system its values are represented in dynes.

Newton:- The force applied is said to be one dyne if it produces acceleration of 1cm/sec^2 and in a body of mass 1Kg.

Dyne:- The force applied is said to be one dyne if it produces acceleration of 1cm/sec^2 in a body of mass 1 gram.

Effects of force:-

Some of the common effects of force are:-

1. A force may move a body at rest. For example, when we kick a football kept on the ground with our foot, the football moves. The force applied by our foot moves the ball.
2. A force may stop a moving body. For example, when a player catches a moving cricket ball, the force applied by player's hands stops the moving ball.
3. A force can change the speed of a body. For example, when a ball is dropped from a certain height, the speed of the ball goes on increasing due to gravitational pull of the Earth on the ball, in the

downward direction. Thus force applied by the Earth in the direction of motion of the ball increases the speed of the ball.

4. A force may change the direction of a moving body. For example, when a moving cricket ball is hit by a bat, the cricket ball moves in a different direction. The force applied by the bat changes the direction of the moving cricket ball.
5. A force may change the size and shape of a body. For example, when we press a rubber ball or a balloon between our two hands, the shape of the rubber ball or balloon changes from spherical to ablong. The forces applied by our hands change the shape of the rubber ball/balloon.

Forces can be classified into two classes:-

1. Contact forces
2. Field force or non-contact force

1. Contact force: A force involving direct contact of two bodies is called a contact force. Examples of contact forces are:

(a) Frictional force: The force which acts to reduce relative motion between the surfaces of contact is called frictional force. When we try to slide a box on a rough surface by pushing it, a force acts parallel to the surface in contact with the floor and opposes the pushing force. This force is called frictional force.

(b) Normal force: if contact between the bodies are perpendicular to the surface in contact the forces are known as normal forces. e.g a wooden block kept on table is in equilibrium. Block applies a downward force on the table due to its weight and table pushes the block upwards. Thus both table and block apply a normal force on each other.

2. Field force: The force which a body applies on another body , when the two bodies are not in contact with each other is called field force or non contact force. Examples are:

(a) Gravitational force: The force of attraction which one body exerts on the other because of their masses is called gravitational force.

(b) Magnetic force and electrostatic force.

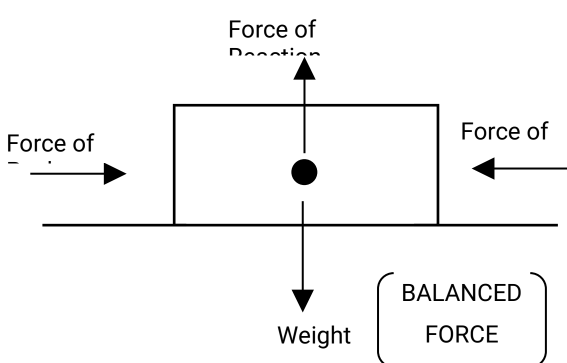
<u>Types of force:-</u> Forces are of main two types, viz.

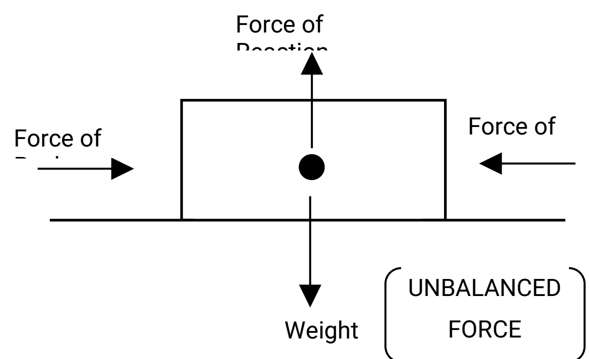
(i). <u>Balanced force:-</u> A force is said to be balanced if the resultant of all the forces acting on a body is equal to 0. A body under the influence of a balanced force does not change its position of rest or uniform motion and appears as if no force is acting on it. For example:

In the game of tug of war, the two teams pull each other in the opposite directions. If the two teams pull the rope with equal force i.e. $F_1 = F_2$, then the rope does not move in either direction. Under this condition, the forces acting on a rope are balanced forces.

(ii). <u>Unbalanced force:-</u> A force is said to be unbalanced if the resultant of all the forces acting on a body is not equal to 0. A body under the influence of unbalanced force changes its position of rest and uniform motion. For example.

In the tug of war, if the force applied by a team is greater than that applied by the other team. Then the members of the weaker team will be pulled towards the stronger team. Thus, the unbalanced forces produce motion.





<u>Newton's Laws of Motion</u>: (1692 – 1772) Newton devised three basic laws based on his name, to describe motion. All these laws are known as Newton's laws of motion and are explained as under:-

Newton's First Law of Motion or Galileo's Law of Inertia:-

It states that, "Everybody continues to remains in the state of rest or uniform motion in a straight line until or unless completed by some external force to change its state of rest or motion". In other words, the first law of motion recognizes that everybody has some inertia i-e the property of a body to remain in a state of rest or uniform motion. This law is accordingly also known as, "Law of inertia". For example:

(i) A book lying on a table will remain there unless and until somebody will come and change its place.
(ii) A cricket ball will remain in motion after hit by the player unless and until the force of friction and the resistance of air stop it and changes its motion into rest.

Inertia:- The word inertia means unchanging. It has been derived from the Latin word inert. It is defined as the property of a body to remain in the state of rest or uniform motion. In other words, inertia may be defined as the property of a body to remain in the state of rest or uniform motion. In other words, inertia may be defined as the inability of a body to change its any state. A heavier body has more inertia than a lighter body. Therefore, we can say that "The larger the mass, the larger is the inertia, and smaller the mass, smaller is the inertia."

In other words we can say that "The mass of a body is a measure of its inertia." It is of three main types:-

(i). Inertia of Rest:- It is the inability of a body to change its rest or its property to remain in rest. This means a body at rest remains at rest and cannot start moving on its own.

(ii). Inertia of Motion:- It is the inability of a body to change its state of motion or its property of a body to remain in the same direction for example Balls bowled by a bowler remain in same direction until it is played of the batsman.

(iii) Inertia of direction:- It is the inability of a body to change by itself

its direction of motion, i.e., a body moving along a straight line will continue to move along the same direction unless some external force compels it to change the direction of motion.

Examples of inertia

Why are passengers thrown in the forward direction when a running bus stops suddenly?

Passengers sitting or standing in a running bus share the motion of the bus. This means, the passengers in a running bus are also moving with the same speed in the same direction. When the running bus stops suddenly, the lower part of the passenger's body comes to rest, while the upper body portion continues to remain in motion. As a result, the passengers are thrown in the forward direction when a running bus stops suddenly.

Why do Passengers tend to fall side ways the bus takes a sharp turn?

When a bus runs along a straight-line path, all the passengers traveling in the bus also move with the same speed in the same direction. When the bus takes a sharp turn, the upper body portion of the passengers still continues to move in the original (straight line) path, while the lower portion tends to turn with the bus. As a result, passengers tend to fall/ lean side ways.

Why should a passenger hold on to a support to prevent himself from swaying in a turning bus?

A person traveling in a bus shears the motion of the bus. When the bus takes a turn, it changes its direction of motion. The passenger due to his inertia of motion, however, continues to move in the original direction. So, if the passenger does not hold on to a support, he will be swayed away.

Why do passengers in a bus tend to fall backward when it starts suddenly?

When a passenger in sitting or standing in a stationery bus, both the bus and the passenger are at rest. When the bus starts moving

suddenly, the lower part of the passenger's body starts moving forward with the bus. The upper part of the body tends to remain in the position of rest due to its inertia of rest. As a result, therefore, the passenger falls or leans backwards.

Similarly a rider on horseback falls backwards when the horse suddenly starts running.

Why does a passenger jumping out of a rapidly moving bus fall forward with his face downwards, if he does not run forward?

A passenger traveling in a bus shares the motion of the bus. Thus, the passenger's body is moving in the direction of the bus with the same speed. When a passenger jumps out of a fast moving bus, his feet on touching the ground come to rest, whereas the upper part of his body continues to move forward due to inertia of motion. As a result, if he does not run forward he falls with his face downwards.

Why can dust be removed from a carpet by shaking it, or by beating it with a stick?

Initially, both the carpet and the dust therein are at rest. When the carpet is shaken, or beaten with a stick, the carpet is set into motion. Due to inertia of rest, the dust particles tend to remain at rest. As a result, the dust particles fall off.

LINEAR MOMENTUM

The product of mass of a body and its velocity is called linear momentum or simply momentum of the body. Its very important physical quantity which measures the quantity of motion in a body. It is a vector quantity and directs in the direction of velocity. It is denoted by p.

Thus $p=mv$

Its S.I unit is $kgms^{-1}$

Newton's Second Law of Motion:-

According to Newton's second law of motion, the rate of change of linear momentum of a body is directly proportional to the external force applied on the body, and this change takes place always in the direction of the applied force.

Now, the rate of change of linear momentum of a body can be obtained by dividing "change in linear momentum' of the body by the 'time taken' for this change. Thus, according to Newton's second law of motion,

$$\frac{\text{change in linear momentum}}{\text{time taken}} \propto \text{force applied}$$

Mathematical formulation of Newton's second law of motion:-

Suppose m = mass of body,

u = initial velocity of the body along a straight line,

F = an external force applied on the body, which is constant in magnitude,

t = time for which the force is applied

v = Final velocity of the body along the same straight line, after t second.

Initial linear momentum of the body, $P_1 = mu$

Final linear momentum of the body, $P_2 = mv$

Change in linear momentum of the body $= p_2 - p_1$

$= mv - mu$

$= m(v - u)$

$$\text{Rate of change of linear momentum} = \frac{\text{change in linear momentum}}{\text{time taken}}$$

$$= \frac{m(v - u)}{t} \qquad \text{........(i)}$$

But $\frac{(v - u)}{t}$ = rate of change of velocity = acceleration of the body = a

Therefore from equation (i), rate of change of linear momentum = ma

According to Newton's second law of motion, rate of change of linear momentum α force applied

Therefore $ma \propto F$

Or $F \propto ma$

Or $F = kma$ …….(ii)

Where k is a constant of proportionality. The value of k depends on the units adopted for measuring the force.

IF we define F = 1, when m = 1 and a = 1 i.e., unit force is that much force which produces unit acceleration in a body of unit mass, then from eqn. (ii)

$$1 = k \times 1 \times 1 \text{ or } k = 1$$

Putting this value of k in eqn. (ii), we get

$$F = ma$$

This is the mathematical form of Newton's second law of motion. It state that

Force acting on a body is the product of mass of the body and acceleration of the body.

<u>Relation between force and acceleration</u>:-

From the Newton's 2nd law of motion, we have:

$$F = m \times a$$

Or, $a = F/m$

From the above equation, it is clear that acceleration produced in a body is directly proportional to the force acting on it and inversely proportional to its mass.

Newton's Third Law of motion:-

It states that, "If a body exerts a force on some other body, then the second body exerts a force of some magnitude on it but in opposite direction". Thus, in other words it states that, "To every action there is an equal and opposite reaction". For example:

1. When a ball is thrown on to a wall, it comes back with the same force and speed.
2. When we pull a spring, it pulls us back with the same force.
3. When we hit a ball to the ground, it comes back at the same speed.

Examples:-

1. When you strike a rubber ball against a hard floor, the ball exerts a force (called action) on the floor. The floor exerts an equal and opposite force (called reaction) on the ball. The rubber ball, being light, rebounds.
2. When a gun is fired, the bullet goes out due to the force applied on it through the trigger (this is action). The gun recoils backward due to the reaction acting on it in the opposite direction. This gives a backward jerk to the shoulder of the gunman.

The change in the momentum of the bullet is equal and opposite to that of the gun. Initially, both the shot and the gun are at rest. So, the momentum produced in the gun is equal and opposite to that produced in the bullet. Thus, the gun is at rest. So, the momentum produced in the gun is equal and opposite to that in the bullet. Thus,

Mass of bullet × speed of the bullet = Mass of the gun × speed of the gun.

Since, the mass of the gun is much greater that that of the bullet, hence the speed of the gun is very small as compared to that of the bullet. Therefore, the gun moves backwards only by small distances

during recoil.

Newton's first law of motion is a special case of Newton's second law:-

Newton's first law of motion can be deduced form Newton's second law of motion.

According to Newton's second law of motion,

$$F = ma$$

$$= \frac{m\ (v\ -\ u)}{t}$$

Or $$F \times t = mv - mu$$

When no external force is applied, $F = 0$

Therefore,

$$mv - mu = 0$$

or $$mv = mu$$

or $$v = u$$

It means the body will continue to move with the same uniform velocity, u throughout the time t, when no external force is applied on the body. Further, if $u = 0$, then v will also be zero. It means if the object is initially at rest, it will continue to be at rest, when no external force is applied on the body.

This is Newton's first law of motion.

Momentum:- It may be defined as the product of mass and velocity of a body and is infact meant for the measure of the motion of a body. Thus,

Momentum = Mass × Velocity

Or, $$P = m \times v$$

Momentum of a body has both magnitude and direction and is therefore a vector quantity. On S.I system, it is measured in $Kg.m/sec^2$ written as $Kg.m/sec^{-2}$.

Relation between force and momentum:-

Consider a body of mass (m) having an acceleration of (a) m/sec^2 .Then, the force exerted by the body (f) can be given by the relation.

$$F = m \,.\, a \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

Let the force applied (*f*) changes the velocity of a body from u m/sec^2 to v m/sec^2 in a time (*t*) sec. Then, the acceleration produced can be given as:-

$$a = \frac{v - u}{t}$$

Now, substituting the values of "*a*" in equation (i), we get

$$F = m \times a$$

$$F = m\,\frac{(v - u)}{t}$$

$$F = \frac{mu - mv}{t}$$

where *mu* = Initial momentum of the body.

and *mv* = Final momentum of the body.

Thus, $force = \frac{Final\ momentum - Initial\ momentum}{time}$

Or $force = \frac{Change\ in\ momentum}{Time\ taken}$

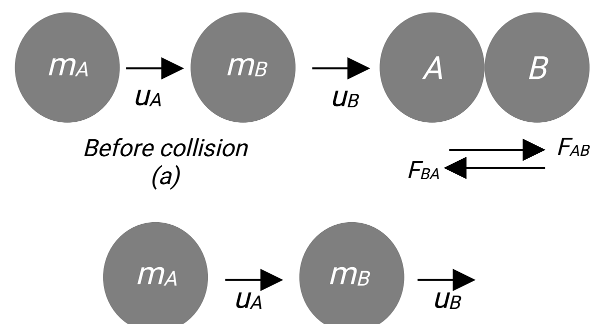
Or *force = rate of change in momentum*

Thus, from the above relation, it is clear that the force applied to a body is directly proportional to the rate of change in momentum produced in the body, when the change in momentum takes place in the direction of force applied. Thus, the relation of force and momentum gives another statement of the Newton's 2nd law of motion.

Law of conservation of momentum:-

According to this law:

When two or more bodies interact with one another, the vector sum of their linear momenta remains



constant (i.e., conserved), and is not affected due to their mutual action and reaction. The only condition is that no external unbalanced forces should be acting on the system of bodies.

We can prove this law by considering an ideal collision experiment between two bodies.

Suppose two objects (two balls A and B, say) of masses m_A *and* m_B are travelling in the same direction along a straight line at different velocities u_A and u_B , respectively. And there are not other external unbalanced forces acting on them. Let $u_A > u_B$ and the two balls collide with each other. During collision which lasts for a time t, the ball A exerts a force F_{AB} on ball B and the ball B exerts force F_{BA} on ball A. Suppose v_A and v_B are the velocities of the two balls A and B after the collision, respectively

Conversion of momentum in collision of two balls

We know the momenta of ball A before and after the collision are mAuA and mAvA, respectively. The rate of change of its momentum (or F_{AB}*, action) during the collision will be* $m_A \frac{v_A - u_A}{t}$

Similarly, the rate of change of momentum of ball B (= F_{BA} or reaction) during the collision will be

$$m_B \frac{v_B - u_B}{t}$$

According to the third law of motion, the force F_{AB} exerted by ball A on ball B (action) and the force F_{BA} exerted by the ball B on ball A (reaction) must be equal and opposite to each other. Therefore,

$$F_{AB} = -F_{BA}$$

Or $$m_A \frac{v_A - u_A}{t} = -m_B \frac{v_B - u_B}{t}$$

$$\frac{m_A v_A - m_A u_A}{t} = \frac{m_B v_B - m_B u_B}{t}$$

This gives $$m_A u_A + m_B u_B = m_A v_A + m_B v_B$$

Since $(m_A u_A + m_B u_B)$ *is the total momentum of the two balls A and B before the collision and* $(m_A v_A + m_B v_B)$ *is their total momentum after the collision, form equation we observe that the total momentum of the two balls remains unchanged or conserved provided*

no other external force acts.

As a result of this ideal collision experiment, we say that the sum of momenta of the two objects before collision is equal to the sum of momenta after the collision provided there is no external unbalanced force acting on them. This is known as the law of conservation of momentum.

Questions

Q. If action is always equal to the reaction, explain how a horse can pull a cart?

Ans. The horse pushes the ground with its foot in backward direction by pressing the ground in a slanting direction. As a result of this action, the ground pushes the horse in the forward direction. Hence the horse pulls a cart.

Q. Why doesn't a truck move if a student pushes it?

Ans. When we push a massive truck parked along the roadside, it does not move. This is because forces of action and reaction never act on one body. There is no question of their cancellation. The truck does not move because the push applied is far less than the force of action between the truck and the road. We also do not move because the force of reaction acting on us is less than force of friction between us and the road.

Q. Why is it advised to tie any luggage kept on the roof of a bus with a rope?

Ans. Any luggage kept on the roof of a bus should be tied with a rope. This is because when the bus starts suddenly, the luggage pieces may fall down due to inertia of rest. Similarly, when the moving bus stops

suddenly, the luggage pieces may fall down due to inertia of motion.

Q. Why a fireman struggles to hold a hose-pipe?
Ans. This is because the stream of water rushing through the hose-pipe in the forward direction with a large speed exerts a large force on the hose-pipe in the backward direction. The force exerted on the hose -pipe in the backward direction is known as the reaction force. This reaction force tends to move the hose-pipe in the backward direction. Therefore, a fireman struggles to hold the hose-pipe strongly to keep it at rest.

Q. Explain why some of the leaves may get detached from a tree if we vigorously shake its branch?
Ans. When we shake vigorously a branch of a tree, some of the leaves may get detached on account of inertia of rest of the leaves. The branch comes in motion and the leaves try to be in the position of rest. Therefore, they get detached.

Q. Why does the fielder pull his arms back while trying to stop or catch a cricket ball?
Ans. When a fielder stops a fast moving cricket ball suddenly, the speed of the ball decreases from a high value to zero in a very short time. Therefore, the retardation (negative acceleration) of the ball will be very large. As a result, the fielder has to apply a large force to stop the ball. The ball in turn exerts a large force on the fielder's hand. So, the fielder's hand may get hurt when he tries to stop / catch a fast moving cricket ball suddenly without moving his hands.

If the fielder stops the ball by gradually pulling his arms/hands back along with the ball, then the same change in speed is brought about in a larger period of time. Therefore, the retardation of the ball will be small. As a result the fielder has to apply lesser force to stop the ball. So, the ball will exert lesser force on the hands of the fielder, and the fielder will not get hurt.

NUMERICAL

1. A rifle of mass 3 kg fires a bullet of mass 0.03kg. The bullet leaves the barrel of the rifle at a velocity of 100m/s . if the bullet takes 0.003 second to move out of the barrel, calculate the force experienced by the rifle due to recoil.

Solution: Let M be the mass of the gun and m be the mass of the bullet.

Total momentum of the rifle + bullet system = M.0 + V.0 =0

= -MV + mv

According to law of conservation of momentum intial momentum = final momentum

0=MV+mv

V= -mv/M

= -0.03*100/3

= -1m/s

Acceleration of the rifle = V-0/t

= -1/0.003 m/s^2

Force =M*A

= 3*-1/0.003

= -1000N

Force is opposite to the direction of velocity of the bullet and has magnitude 1000N